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Life Safety Evaluation of Large Populations with Mixed-Abilities

Shuji Kakegawa and Yoshiro Yashiro
Institute of Technology, Shimizu Corporation
3-4-17 Etchujima Koto-ku, Tokyo 135, Japan

Manabu Ebihara
Izumi Research Institute, Shimizu Corporation
2-2-2 Uchisaiwai-cho Chiyoda-ku, Tokyo 100, Japan

Abstract

The authors had developed an evacuation model which can predict evacuation of large populations with mixed abilities. The advantages of the model are: 1) to handle the evacuation of persons with mixed abilities, 2) to change egress routes in accordance with local environmental conditions, 3) to handle contra-flows and overtaking which occur between evacuees, 4) to handle interactions between individuals in a crowd and 5) to handle total evacuation of a multi-story building. In this study, we describe the outline of the model and its application. In order to clarify the influence of variation of egress capabilities on evacuation time, some case studies are carried out. After that, we clarify the problems in planning life safety for large populations with mixed-abilities against a fire.

1. Introduction

In recent years, large-scale buildings have increased especially in urban areas in Japan. In Tokyo, there are 68 high-rise buildings which are over 100 meters tall in 1994[1]. Large-scale buildings have some problems in total evacuation from a fire, because they have a large population with mixed-abilities. Some important aspects of the evacuation from large-scale buildings are summarized as follows; 1) a long period of total evacuation time via staircases, 2) congestion of mixed-ability population and 3) rapid smoke spread to the upper floors via vertical compartments.

In Japan, high-rises and other specified occupancies must meet requirements according to *The Guide for Building Fire Safety Planning*[2]. It requests life safety evaluation by calculating some egress times on the fire floor at assigned limits[3]. However, in planning buildings for large populations with mixed-abilities, more detailed information will be needed to clarify problems in planning to improve. If a building designer or an engineer supposes to evaluate evacuation safety for those building, detailed simulation of evacuation behavior will play important roles.

In predicting evacuation behavior of mixed abilities, interactions between individual evacuees is one of the most important factors. Recently, some attempts have been made to predict individual egress behavior, for example, EXIT89[5], SIMULEX[6], EvacSim[7]. These models are intended to handle individual egress movement and it enables us to examine the influence of egress capabilities of evacuees on life safety.

To evaluate life safety of the disabled in health care facilities, the authors had developed an evacuation model which can predict mixed population evacuation[4]. We have modified the model in order to handle larger number of individual people with mixed-abilities. In this study, we describe the evacuation model which is modified for large populations with mixed-abilities and clarify the problems in planning life safety for them against a fire.

2. Model Description

2.1 Characteristics and Assumptions

The evacuation model is a deterministic simulation program implemented by the object-oriented computer language, C++. The model is an advanced version of the previous one, which was developed for health care facilities[4]. The model comprises three sub-models; the space model, the human model and the smoke model. The simulation process corresponds to information exchange between the sub-models. Figure 1 shows the evaluation process for evacuation safety using the evacuation model. These sub-models play roles as follows:

1) Space Model; for modeling all rooms of a building and connection between rooms,
2) Human Model; for modeling evacuees and their decision making process to determine positions of them and their evacuation routes,
3) Smoke Model; for modeling the spread of smoke in a building.

The advantages of the evacuation model are: 1) to handle the evacuation of persons with mixed abilities, 2) to change egress routes in accordance with local environmental conditions, 3) to handle contra-flows and overtaking which occur between evacuees, 4) to handle interactions between individuals in a crowd and 5) to handle total evacuation of a multi-story building. The advantages which are expanded in this version correspond to items 4) and 5) as mentioned above. However the previous version can handle the rescuers' behavior, the current version abbreviates them for simplicity of calculation. Psychological factors influencing evacuation behavior are not considered in the model.

2.2 Egress Behavior Modeling

In choosing egress routes, occupants select two types of targets; a short term target and a long term target. The short term target indicates a place which people should pass through, for example, a door. The long term target indicates a place where people finally escape. People continue evacuation until they reach a long term target. Rules for choosing a target and determining the position at the next step are described in the previous paper[4]. In the Human Model, evacuees are modeled according to the following parameters: spatial requirement of a person, travel walking speed and type of egress route finding.

(1) Spatial Requirement of a Person

In the model, all people are modeled in circles individually to consider human spatial requirement. The diameter of a circle is determined as 0.4 meter with consideration of the size of body. Using the distance between evacuees and spatial requirements, interactions between people are assessed. It is an important factor in predicting congestion or contra-flows of a crowd.

(2) Travel Walking Speed

In this model, fluctuations in individual walking speed is defined due to the crowd density. Relationship between the walking speed and density is defined as following equation with reference to the previous studies, for example, by Predtechenskii & Milinskii[8]:

$$Vh = Vmax / p \qquad (p>=1.0 \text{ person/m}^2) \qquad (1)$$
$$Vh = Vmax \qquad (p< 1.0 \text{ person/m}^2) \qquad (1)'$$

where Vh is horizontal walking speed, $Vmax$ is maximum horizontal walking speed and p is crowd density. $Vmax$ varies from 0.5 to 1.5 meter per second according to the egress capabilities of occupants. p is calculated for the area of half circle having a radius of 3.0 meters around an evacuee as illustrated in Figure 2(a). If p is below 1.0 in person per square meter, Vh is constant at $Vmax$.

If crowd density of the adjacent room around a door is high, people can not merge and have to queue in front of the door. To model merging of crowd flows at a door, queuing is assumed to be caused when crowd density is over six person per square meter in the area of half circle having a radius of 1.0 meters around him/her (see Figure 2(b)).

(3) Type of Egress Route Finding

Egress route finding is modeled according to the results of a survey to occupants of a sixty story complex high-rise building in Tokyo[1]. The survey was carried out by asking questionnaire about the egress route finding to 757 respondents. They include 193 office workers, 464 visitors of a department store or a hall and 100 visitors of a hotel. From the survey, occupants are categorized as three types in egress route finding;

1) occupants who evacuate according to the self-judgment (Type I),
2) occupants who evacuate following the instruction (Type II),
3) occupants who move depending on the other people (Type III).

In the model, Type I occupants always choose the nearest door or exit. Type II occupants determine egress direction according to the guide light which is modeled in the Space Model. Type III occupants follow the neighbors.

2.3 Multi-Story Evacuation Modeling

The model of this version can take into account total evacuation of a multi-story building. Staircases are modeled as one room like a corridor which has the same width of the stair. Steps on a staircase are not considered. Travel walking speed in a staircase is reduced in comparison with the horizontal walking speed as shown in the following equation:

$$Vs = C\ Vh \tag{2}$$

where Vs is horizontal component of walking speed in staircases, Vh is horizontal walking speed on a floor and C is a speed reduction factor (=0.8).

2.4 Smoke Spread Modeling

To predict the spread of smoke, the two-layer zone model, BRI2, is employed[9]. Using the results of smoke simulation, physiological impact of smoke at time t, $S(t)$, is calculated for each room. $S(t)$ is given by the following equation:

$$S(t) = \sum_{ts}^{t} (\Delta T)^2 \delta t \tag{3}$$

where δt is time interval for simulation (in this study, δt=1.0 second), ts is the smoke-exposure starting time, and ΔT is the temperature rise in the smoke layer. If $S(t)$ in a room i becomes over 4,000, the room i is assumed to reach the critical egress time[9], te, when any persons in the room i are assumed to become victims. After falling under te, the room is blocked due to smoke and anyone cannot enter there. In this model, the influence of people's movement on smoke movement cannot be considered because the two-layer zone model is separated from the evacuation model.

3. Model Validation

To validate the evacuation model, the predicted results of total evacuation are compared in part with a previous evacuation drill in a high-rise building[9]. A hypothetical building for model validation consists of seventy floors of office space. Initial occupant load is 0.125 persons per square meter at the average, which is derived from *The Guide for Building Fire Safety Planning*[2].

Figure 3 illustrates a typical floor plan of the building. There are 272 occupants on each floor. The ground floor is used for a lobby and there are no occupants initially.

The building where the evacuation drill were carried out consists of seventeen floors of office space. There were 1,242 occupants in the building.

The flow rate at an exit door on the first floor, crowd density and walking speed in a staircase are chosen as the indexes to compare the results with the one of the observed evacuation drill. Smoke spread and variation of egress capabilities are not considered. Horizontal walking speed of an evacuee is set at 1.0 meter per second.

Table 1 shows the comparison of the predicted and the observed evacuation. The predicted flow rate at the exit door of the staircase agreed approximately with the observed one. Modeling individuals influences a good agreement of the results. Although the horizontal component of walking speed of the predicted evacuation is lower than the observed one, it does not so much influence the predicted total evacuation time. This is because flow rate at the exit door much influences the total evacuation time in these cases. From the results, it is considered that the model can be used to predict the total evacuation in a multi-story building.

4. Application of the Model

In order to clarify the influence of egress capability profiles of occupants, some case studies were carried out. In the case studies, types of egress route finding and travel walking speed are chosen for the parameters of egress capabilities. A building for application has the same floor plan as the one for model validation. It consists of five floors of office space. In these cases, all occupants in the building are assumed to start evacuation at the same time. For simplicity, smoke movement is not considered in the case studies.

4.1 Case 1: Influence of Variation of Walking Speed

For the first example, influence of egress capability profiles in walking speed are examined. Table 2 shows a number of occupants on one floor for three different cases.

Figure 4(a) shows relationship between time and a total number of evacuated occupants. If rates of occupants at slow speed are higher, total evacuation time becomes longer remarkably. It takes about 1.8 times in total evacuation of Case 1-1 in comparison with the one of Case 2-3. In general, population profiles in Case 1-1, 1-2, 1-3 almost correspond to an office, a department store and a hospital, relatively. If the disabled have to evacuate from large-scale building, it possibly takes a long time in total evacuation and they may be in more dangerous situation.

Figure 5(a) shows an average crowd density in a staircase. The average crowd density represents a number of people in unit area of staircase where people are evacuating. The highest density becomes about 3.0 persons per square meter in Case 1-1 and 1-2. It is approximately equal to 1.3 persons per one stair step. Contrary to these cases, peak crowd density in Case 1-3 becomes about 5.8 persons per square meter. It is over twice as the results of the previous experiment carried out by Paul[10]. In the case where rates of occupants at fast speed are high, no consideration of stair steps in modeling staircases seems to influence the crowd density in the staircase. In real evacuation, stair steps restrict the evacuation flow.

4.2 Case 2: Influence of Type of Egress Route Finding

For the second example, influence of egress capability profiles in types of egress route findings are examined. Table 3 shows a number of occupants on one floor for three different cases. In the case studies, occupant Type I and II are supposed to be the same, because evacuation instruction was not considered in these cases.

Figure 4(b) shows relationship between time and a total number of evacuated occupants. Although profiles of occupants in type of egress route finding are different, total evacuation times were almost the same. In the case study, congestion around the door of the staircase offset their delay due to the relatively simple egress route. Occupants who depend on the other people delayed to start evacuation, because their egress targets were uncertain in the beginning of the evacuation. In more geometrically complex building, for example, a department store, types of egress route finding will much influence total evacuation time.

5. Conclusions

The proposed evacuation model of the advanced version can handle the total evacuation of large population with mixed-abilities. By comparison between the predicted and the observed evacuation, it is considered that the model is validated for the observed drill evacuation.

From the results of applications, it is concluded that variation in walking speed much influences on total evacuation time than types of egress route finding in a building which has simple egress routes. Large-scale buildings have much difficulty in total evacuation as shown in the case of World Trade Center Bombing in 1993, especially for the disabled[11]. The strategies of total evacuation, for example, partial evacuation, will be one of the important factors to ensure life safety of mixed-ability large population.

The evacuation simulation provides a quantitative evaluation method of life safety to aid building designer. It can possibly be applied to the performance based design of a building to compare the effects of fire safety provisions. To use the evacuation model in planning buildings, valid fire and evacuation scenarios for evaluating life safety should be determined in reference to previous fire accidents.

Acknowledgements

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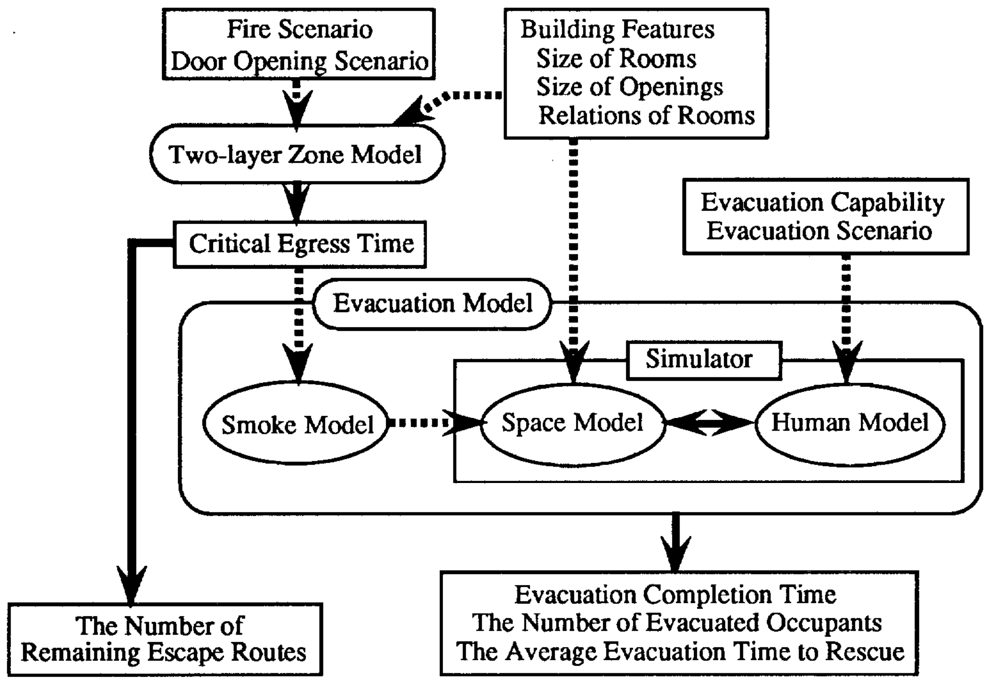
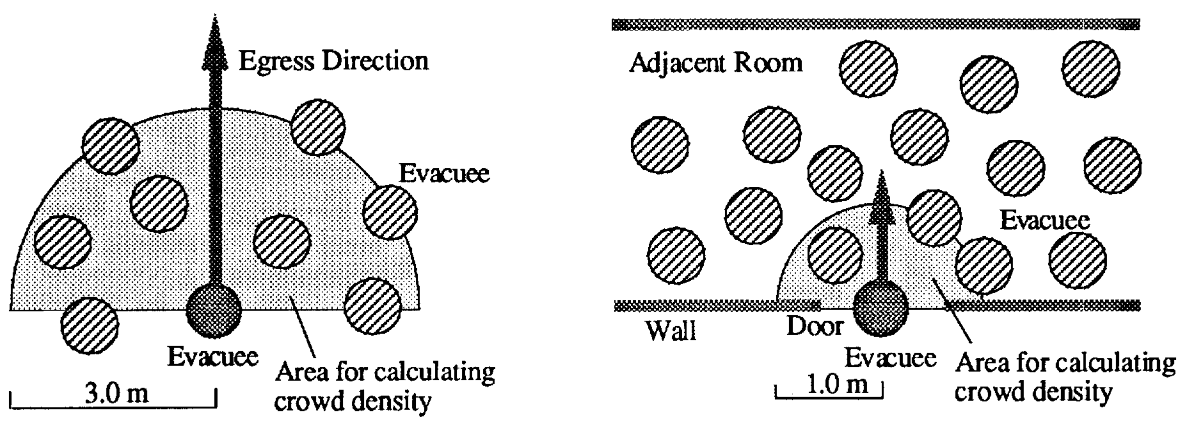


Figure 1. Life Safety Evaluation Process Using the Evacuation Model



(a) Speed Reduction Assessment in a Crowd (b) Flow Mergence Assessment at a Door

Figure 2. Obstruction Zone for Egress Behavior

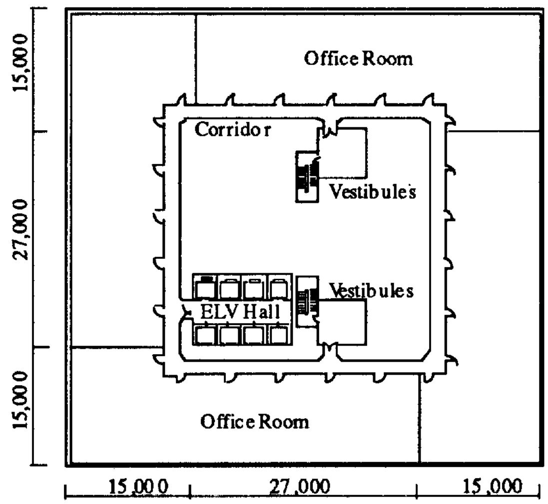
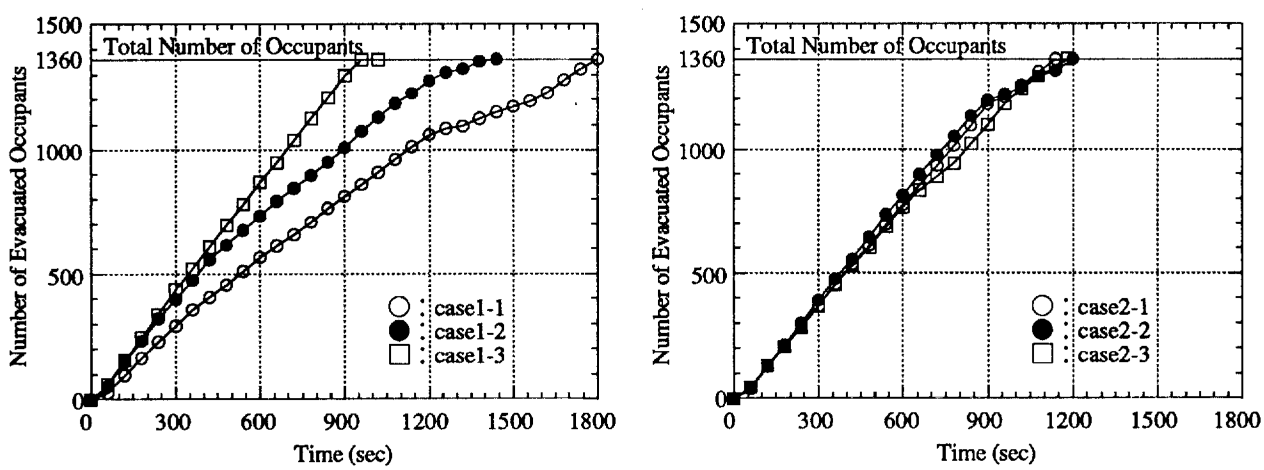
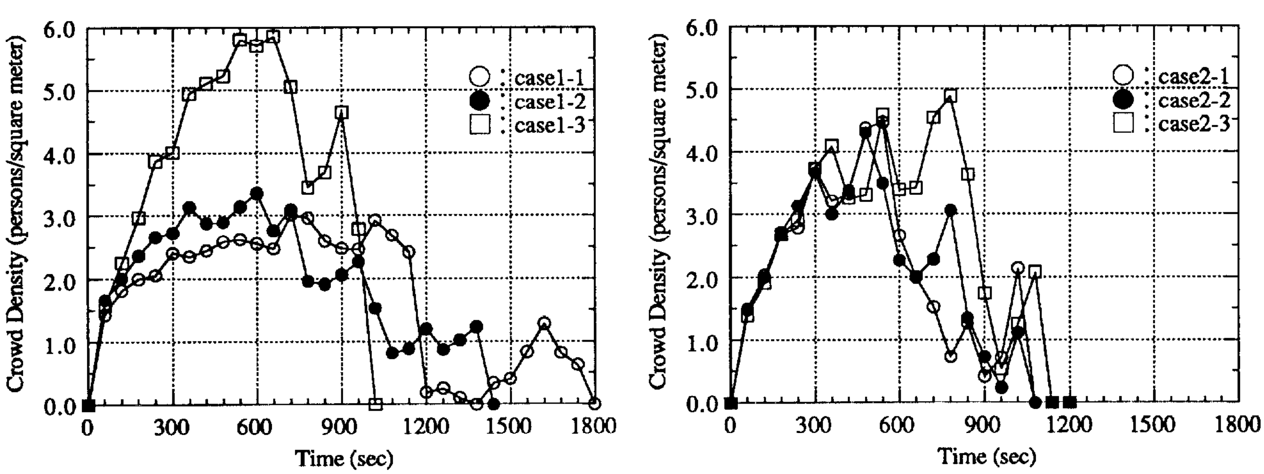


Figure 3. Typical Floor Plan for Applications of the Evacuation Model



(a) Case 1: influence of walking speed (b) Case 2: influence of type of route finding

Figure 4. Relationship between Time and Number of Evacuated Occupants



(a) Case 1: influence of walking speed (b) Case 2: influence of type of route finding

Figure 5. Relationship between Time and Average Crowd Density in a Staircase

Table 1. Comparison between Observed and Predicted Evacuation

	The Observed Evacuation [9]	The Predicted Evacuation
Stories of the building	17	70
Populations per one staircase (persons)	621	9520
Stair width (meter)	1.2	1.4
Exit door width of the staircase (meter)	0.88	0.9
Flow rate at a door on the first floor (persons/meter/second)	0.80~0.89	0.83
Maximum crowd density (persons/square meter)	4	3.5
Horizontal component of walking speed in a staircase (meter/sec)	0.35~0.5	0.15~0.3

Table 2. Egress Capability Profiles in the Case Studies (Case 1)

Maximum Travel Walking Speed : Vmax	Number of Occupants on each Floor		
	Case 1-1	Case 1-2	Case 1-3
0.5 (meter/sec)	177 (65%)	91 (33%)	— (—)
1.0 (meter/sec)	95 (35%)	90 (33%)	95 (35%)
1.5 (meter/sec)	— (—)	91 (33%)	177 (65%)

Table 3. Egress Capability Profiles in the Case Studies (Case 2)

Type of Egress Route Finding	Number of Occupants on each Floor		
	Case 2-1	Case 2-2	Case 2-3
Self-Judgment (Type I & II)	245 (90%)	190 (70%)	136 (50%)
Dependants (Type III)	27 (10%)	82 (30%)	136 (50%)

Discussion

John Hall: Have you compared the modeling approach that you've used to other evacuation models that have been developed and reported?

Shuji Kakegawa: No, not yet.